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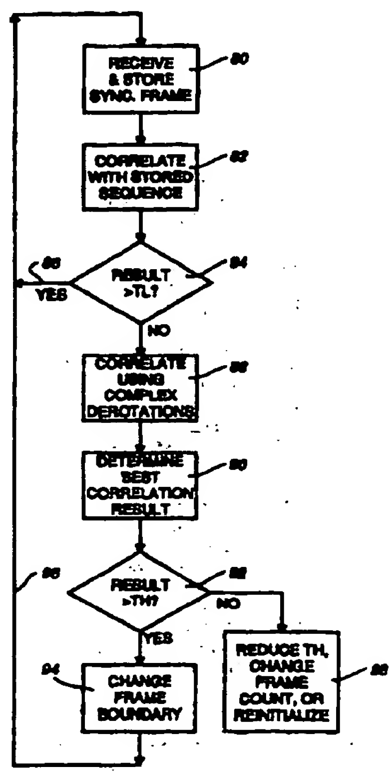
(54) Title: FRAME SYNCHRONIZATION IN MULTICARRIER TRANSMISSION SYSTEMS

(57) Abstract

A discrete multitone modulation transmission system is described in which frame synchronization is monitored at the receiver by correlating frequency domain complex amplitudes of a synchronizing frame with a stored synchronizing pattern. If the correlation result falls below a threshold, indicating a loss of frame synchronization, a plurality of correlations are performed, in each case using the stored complex amplitudes of the synchronizing frame multiplied by a respective complex value representing a respective complex derotation corresponding to a respective possible time shift of the synchronizing frame. The best correlation result, if it exceeds another threshold, indicates a time shift for restoring frame synchronization, this being possible before the next synchronizing frame is received.



FRAME SYNCHRONIZATION IN MULTICARRIER TRANSMISSION SYSTEMS

This invention relates to transmission systems using multicarrier modulation, and is particularly concerned with frame synchronization in such systems, referred to below for brevity simply as multicarrier systems.

Background of the Invention

The principles of multicarrier modulation are described for example in "Multicarrier Modulation For Data Transmission: An Idea Whose Time Has Come" by John A. C. Bingham, IEEE Communications Magazine, Vol. 28, No. 5, pages 5-14, May 1990. As is known, in a transmission system using multicarrier modulation, FDM (frequency division multiplexed) sub-carriers spaced within a usable frequency band of a transmission channel, forming a set of sub-carriers, are modulated at a block or symbol transmission rate of the system. The bits of input data for transmission within each block or symbol period are allocated to the sub-carriers in a manner which is dependent upon the signal-to-noise ratios (SNRs) of the sub-carriers, typically so that the bit error rates of the sub-carriers, as monitored at the receiver, are substantially equal. As a result, the different sub-carriers carry different numbers of bits in each symbol period. With an appropriate allocation of bits and transmit powers to the sub-carriers, such a system provides a desirable performance.

One particular form of multicarrier modulation, in which the modulation is effected using a discrete Fourier transform, is referred to as discrete multitone, or DMT, modulation. The related applications referred to above disclose details of multicarrier systems using DMT modulation.

As in any communication system, it is necessary to establish and maintain synchronization between the transmitter and receiver of a DMT or other multicarrier system. Frequency synchronization is conveniently provided in a DMT system by using one of the multiple tones as a pilot tone to control a phase locked loop at the receiver, as indicated in Standards Committee Contribution T1E1.4/93-022 by J. S. Chow et al. entitled "DMT Initialization: Parameters Needed For Specification In A Standard", March 8, 1993. This reference also outlines other initialization processes of a DMT system, including the allocation of bits to sub-carriers or tones of the system.

In addition to this frequency synchronization, synchronization of the transmitted blocks or symbols of data is required. This is referred to herein as frame synchronization, each frame corresponding to one block or symbol of the multicarrier system, for consistency with the same term as used in single carrier transmission systems. It should

results a time shift for restoring frame synchronization; and adjusting a frame boundary in accordance with the determined time shift to restore frame synchronization.

For a discrete multitone modulation transmission system, the method preferably includes the steps of: using a tone having a predetermined frequency for frequency synchronization between a transmitter and a receiver of the system; at the transmitter, converting complex amplitudes in the frequency domain into time domain values using an N-point Inverse Fast Fourier Transform; sampling time domain values at the transmitter at a sampling frequency which is j times the predetermined frequency, where j is an integral power of two; and at the receiver, converting time domain values into complex amplitudes in the frequency domain using an N-point Fast Fourier Transform; each of said complex derotations corresponding to a respective one of N / j time shifts within the duration of one frame. This is particularly advantageous if the synchronizing frame is periodically transmitted once every Q frames, where Q is an integer greater than N / j, because it enables frame synchronization to be restored between two consecutive synchronizing frames.

Preferably each correlation result is produced by multiplying each complex amplitude by a corresponding complex amplitude from the stored information representing the synchronizing pattern, and summing the real parts of the complex products. The method preferably includes the step of weighting the complex amplitudes being multiplied, the weighting for each complex amplitude being multiplied preferably being dependent upon a signal-to-noise ratio of a multicarrier channel associated with the respective complex amplitude.

Another aspect of this invention provides a multicarrier modulation transmission system receiver comprising: a Fast Fourier Transform (FFT) unit for transforming time domain values into complex amplitudes in the frequency domain; a buffer for supplying received time domain values to the FFT unit in accordance with a frame boundary; a correlator for correlating complex amplitudes of a synchronizing frame of the system with a synchronizing pattern stored at the receiver to produce a correlation result; and a control unit responsive to the correlation result being below a threshold value to adjust the frame boundary by a time shift determined by performing a plurality of correlations between the stored synchronizing pattern and the complex amplitudes in each case multiplied by a respective complex value representing a respective complex derotation of the complex amplitudes corresponding to a respective time shift of the synchronizing frame, and selecting the best correlation result.

The downstream signal on the path 20 is divided into frames and encoded by the coder 22 into frequency domain multicarrier symbols which are supplied to the IFFT unit 26. Each frame of data is represented by a respective multicarrier symbol, which comprises a complex amplitude (i.e. two amplitudes, for real and imaginary signal components) for each of a number of sub-carriers or tones of the system. For example, the system may use 256 discrete tones or sub-carriers with frequencies of $n \times 4.3125$ kHz, where n is a number of the tone or carrier from 1 to 256. Each tone amplitude is allocated a variable number of bits of the signal, in accordance with a bit allocation scheme which for example can be as described in the related application by R. R. Hunt et al. referred to above. The number of bits allocated to each tone amplitude in each multicarrier symbol period of for example about 250 μs can be zero (i.e. the tone is not being used for the signal) or can vary from a minimum number, for example 2 bits, to a maximum number, for example in a range from 10 to 16 bits.

For frame synchronization as further described below, a synchronizing frame containing a synchronizing sequence generated by the source 24 is periodically inserted into the data flow from the coder 22 to the IFFT unit 26 (a time domain version of the synchronizing sequence could alternatively be inserted between the units 26 and 28). For example, a synchronizing frame is provided as every Q = 69-th frame or multicarrier symbol, so that each synchronizing frame is followed by 68 data frames. The synchronizing sequence is for example a pseudo-random sequence as described further below, the same sequence being provided for each synchronizing frame.

At the input to the IFFT unit 26, one specific tone in every frame is reserved as a pilot tone and carries no information, thereby providing a transmitted pilot tone which serves for frequency synchronization as described further below.

Each frequency domain multicarrier symbol is transformed into a time domain multicarrier symbol by the IFFT unit 26. The time domain multicarrier symbol thus comprises 512 real-valued time domain samples, which are supplied to the cyclic prefix adder 28. For each multicarrier symbol, the cyclic prefix adder 28 supplies a resulting serial stream of for example 544 real-valued time domain samples to the DAC and filter unit 30, which converts these samples into filtered analog signals which are transmitted via the hybrid circuit 14 to the transmission path 18. The 544 samples are constituted by the 512 samples supplied by the IFFT unit 26, prefixed by a repetition of the last 32 of these samples added by the cyclic prefix adder 28. The use and benefits of a cyclic prefix added in this manner are known for example from "A Discrete Multitone Transceiver System For HDSL Applications" by J. S. Chow et al., IEEE Journal on Selected Areas in Communications, Volume 9, No. 6, pages 895 to 908, August 1991.

The pilot tone can have a constant phase, or it can carry over successive multicarrier symbols a specific phase pattern or long pseudo-random sequence which is known to both the transmitter and the receiver. The IFFT unit 26 is supplied with a complex amplitude for the pilot tone which represents the desired contents of the pilot tone. For simplicity and convenience, it is assumed here that the pilot tone has a constant phase, and accordingly the IFFT unit 26 is supplied with a constant complex amplitude, representing this constant phase, for the pilot tone.

The receiver 12 includes a voltage controlled crystal oscillator (VCXO) 46 which produces on a line 48 a sampling clock signal for the ADC in the unit 32, synchronized to the 2.208 MHz sampling frequency of the transmitter 10 by a control loop which includes a phase comparator 50 and digital and analog control loop filters represented by a unit 52. The FEQ and decoder unit 36 supplies the phase information of the received pilot tone via a line 54 to the phase comparator 50, and a stored reference phase is also supplied to the phase comparator 50 from a store 56. The phase comparator 50 produces at its output a digital phase error control signal which is filtered by digital and analog filters in the unit 52 to produce an analog control voltage; this is used to control the VCXO 46 to maintain frequency synchronization.

As explained in the background of the invention, frame synchronization of the transmitted multicarrier symbols of data must also be maintained between the transmitter and receiver. In other words, the same frame boundaries as are used for the multicarrier symbols at the input to the IFFT unit 26 in the transmitter 10 must be used for the FFT unit 38 in the receiver 12. In the receiver 12 the frame boundaries are used by the buffer 36 to determine which sequences, each of 512 time domain samples, are supplied to the FFT unit 38 to be transformed into the respective frequency domain multicarrier symbols.

As described above, in the transmitter 10, every 68 data frames are supplemented by a synchronizing frame, thereby forming a superframe of $Q = 69$ consecutive frames or multicarrier symbols. This number Q is selected to provide a balance between data carrying capacity of the system (for which a high value of Q is preferred) and frame resynchronization time (for which a low value of Q is preferred). The synchronizing frame contains pseudo-random data which can be applied to the tones of the synchronizing frame multicarrier symbol in any of a variety of different ways. A description of one of these ways, given for example, follows.

In the transmitter 10, a binary pseudo-random sequence of length 512 is produced by the source 24 in accordance with the equations:

$$x[p] = 1 \qquad \text{for } p = 1 \text{ to } 9$$

$$x[p] = x[p-4] \oplus x[p-9] \qquad \text{for } p = 10 \text{ to } 512$$

synchronizing sequence from the source 58 is supplied to the correlator 60, a complex derotation multiplier 66 for supplying to the correlator 60 the received synchronizing frame contents multiplied by complex derotation values as described below, and a frame synchronization decision unit 68. The unit 68 is responsive to correlation results produced by the correlator 60 to determine the presence or absence of frame synchronization and, via a path 70, to make corrective changes to the frame boundaries used by the buffer 36 when necessary as described below.

When the transmission system including the transmitter 10 and the receiver 12 is initialized, frame synchronization is established in a manner for example as discussed below. In subsequent normal operation, frame synchronization is maintained without any change of frame boundaries being required. As described below, in this normal operating situation the correlator 60 and decision unit 68 monitor the frame synchronization. In the event of a loss of frame synchronization (in the presence of frequency synchronization, indicating that the receiver 12 is receiving a signal via the path 18), frame synchronization must be restored. While this can be done (as in the prior art) by re-initializing the system, this is very undesirable because the initializing process is relatively slow, for example taking about 20 seconds, resulting in a substantial interruption in the operation of the system.

An actual loss of frame synchronization may arise for example as a result of a printed circuit card containing the transmitter 10 being pulled from an equipment rack (resulting in a loss of signal, and frequency synchronization, at the receiver 12) and then being reinserted (the signal and frequency synchronization thereby being restored at the receiver). A loss of frame synchronization may also be indicated by the monitoring in the event that there is excessive noise which produces a poor correlation result, even though there is no actual loss of frame synchronization. In this case, no frame resynchronization is necessary or desired. The invention permits a distinction to be made between these situations, and in the event of an actual loss of frame synchronization generally enables frame synchronization to be restored, and thereby maintained without any re-initialization of the system, within a very short period for example of less than about 100 ms.

The operation of the components 58 to 68 is described further below with additional reference to the flow chart in Fig. 2.

In a frame synchronized state, as shown by a block 80 in Fig. 2 the received contents of each synchronizing frame, i.e. each 69-th frame or multicarrier symbol, are supplied from the output of the FEQ in the unit 40 and stored in the store 62. It is observed that these contents are complex amplitudes in the frequency domain, representing the complex amplitudes of the tones of the synchronizing frame. As shown

avoided. In addition, although not shown in Fig. 2, a counter may be provided for requiring repeated failures of the correlation result to exceed the threshold TL in successive synchronizing frames before a loss of frame synchronization is determined.

In the event that the correlation result does not exceed the threshold TL (in the requisite number of, e.g. 2, successive synchronizing frames), a block 88 in Fig. 2 is reached.

As represented by the block 88 and further described below, in each of the next 64 data frames, following the synchronizing frame for which a loss of frame synchronization has been determined, the correlator 60 performs a correlation of the received synchronizing frame contents from the store 62, multiplied in the complex derotation multiplier 66 by a respective set of complex derotations, with the synchronizing sequence from the source 58 weighted as described above. Consequently, the correlator 60 produces 64 correlation results, one in each of these 64 data frames. As shown by a block 90 in Fig. 2, the decision unit 68 determines a best one of these correlation results, and as shown by a block 92 in Fig. 2 determines whether this exceeds a resynchronization threshold TH. The threshold TH is set at a higher level than the threshold TL, for example at about half the maximum possible correlation result for a frame synchronized state, so that false resynchronization results are substantially avoided. Again in this case, but not shown in Fig. 2, a counter may be provided to require repeated similar results from the processes of the blocks 88 to 92 in successive superframes before a resynchronization is effected.

In response to the correlation result exceeding the threshold TH as determined in the block 92, a block 94 in Fig. 2 is reached in which the unit 68 changes the frame boundary in a single step, by control of a pointer in the buffer 36 via the path 70, as described further below. This change can be effected during the remaining 68 - 64 = 4 data frames, so that resynchronization is effected before, and can be confirmed with, the next synchronizing frame as shown in Fig. 2 by a path 96 from the block 94 to the block 80. Thus resynchronization in response to a detected loss of frame synchronization can be effected in a single superframe, or in a few superframes if the counters mentioned above are also provided, whereby frame synchronization is substantially continuously maintained. For example, with the sampling frequency of 2.208 MHz, 544 time domain samples in each frame, and 69 frames in each superframe as described above, the superframe period is 17 ms. If both of the counters mentioned above are provided to have a required count of 2, the loss of frame synchronization is detected and resynchronization as described above is completed within four superframes, or 68 ms.

Thus for the block 88 in Fig. 2, each of the 64 data frames referred to above is used for calculation of a correlation result for a respective one of the 64 possible time shifts m. In the multiplier 66, the complex amplitude for each tone n supplied from the store 62 is multiplied by the respective complex derotation W_N^{-mn}, and the resulting products are correlated in the correlator 60 with the weighted complex amplitudes of the synchronizing sequence supplied from the store 58 via the weighting multiplier 64, the real parts of the correlation products being summed to produce the correlation result for the respective time shift m. The correlation process is sufficiently accurate that, in the event that the loss of frame synchronization is due to one of the possible time shifts m being evaluated, the correlation result for that time shift exceeds the threshold TH whereas the correlation results for all other possible time shifts are much less than the threshold TH. The decision unit 68 thereby reliably determines the time shift m which has produced the loss of frame synchronization, and via the path 70 as described above adjusts the pointer of the buffer 36 in a single step to correct this time shift, whereby frame synchronization is restored. This resynchronization is effected without any searching process for the synchronizing sequence.

In the event that no correlation result produced at the block 88 exceeds the threshold TH, then as indicated above this threshold can be lowered, or it can be concluded that a larger time shift has caused the loss of frame synchronization. In the latter case, time shifts greater than one frame can be accommodated by changing the frame count to examine a different frame for the synchronizing sequence, the above steps then being repeated for the different frame count, and this search being continued for different ones of the 69 frames until the threshold TH is exceeded. Alternatively, the system may be re-initialized. In either case a significant time delay is involved in restoring frame synchronization, but as stated above this event is unlikely in practice.

Frame synchronization must be established on initializing the system, as indicated above. The initializing process includes a training method for the TEQ 34 in the receiver 12, as described in an article by J. S. Chow et al. entitled "Equalizer Training Algorithms for Multicarrier Modulation Systems", 1993 International Conference on Communications, pages 761-765, May 1993. At the end of the training of the TEQ 34, an equalized channel response b and an equalizer response (i.e. equalizer coefficients) w are obtained in the time domain by transformation by an IFFT. The relative offset between the starting locations of b and w in the time domain determines the desirable delay for the received signal, which in turn determines the multicarrier symbol or frame boundary at the receiver which is used to provide initial frame synchronization.

WHAT IS CLAIMED IS:

1. A method of maintaining frame synchronization in a multicarrier modulation transmission system in which a synchronizing frame containing a synchronizing pattern is periodically transmitted, comprising the steps of:

storing complex amplitudes of the synchronizing frame;

correlating the complex amplitudes of the synchronizing frame with stored information representing the synchronizing pattern, thereby to produce a correlation result; and

determining whether the correlation result falls below a threshold value, indicating a loss of frame synchronization, and in this event:

performing a plurality of correlations between the stored information and the stored complex amplitudes in each case multiplied by a respective complex value representing a respective complex derotation of the stored complex amplitudes, each complex derotation corresponding to a respective time shift of the synchronizing frame, thereby to produce a plurality of correlation results each corresponding to a respective time shift;

determining from the plurality of correlation results a time shift for restoring frame synchronization; and

adjusting a frame boundary in accordance with the determined time shift to restore frame synchronization.

2. A method as claimed in claim 1 wherein each correlation result is produced by multiplying each complex amplitude by a corresponding complex amplitude from the stored information representing the synchronizing pattern, and summing the real parts of the complex products.

3. A method as claimed in claim 2 and including the step of weighting the complex amplitudes being multiplied.

4. A method as claimed in claim 3 wherein the weighting for each complex amplitude being multiplied is dependent upon a signal-to-noise ratio of a multicarrier channel associated with the respective complex amplitude.

5. A method as claimed in claim 1 wherein the step of determining from the plurality of correlation results a time shift for restoring frame synchronization comprises determining a best correlation result from the plurality of correlations and selecting the

13. A method as claimed in claim 7 wherein each correlation result is produced by multiplying each complex amplitude by a corresponding complex amplitude from the stored information representing the synchronizing pattern, and summing the real parts of the complex products.

14. A method as claimed in claim 13 and including the step of weighting the complex amplitudes being multiplied.

15. A method as claimed in claim 14 wherein the weighting for each complex amplitude being multiplied is dependent upon a signal-to-noise ratio of a multicarrier channel associated with the respective complex amplitude.

16. A multicarrier modulation transmission system receiver comprising:

a Fast Fourier Transform (FFT) unit for transforming time domain values into complex amplitudes in the frequency domain;

a buffer for supplying received time domain values to the FFT unit in accordance with a frame boundary;

a correlator for correlating complex amplitudes of a synchronizing frame of the system with a synchronizing pattern stored at the receiver to produce a correlation result; and

a control unit responsive to the correlation result being below a threshold value to adjust the frame boundary by a time shift determined by performing a plurality of correlations between the stored synchronizing pattern and the complex amplitudes in each case multiplied by a respective complex value representing a respective complex derotation of the complex amplitudes corresponding to a respective time shift of the synchronizing frame, and selecting the best correlation result.

17. A receiver as claimed in claim 16 and including a multiplier for weighting the synchronizing pattern in dependence upon signal-to-noise ratios of the multicarrier channels.

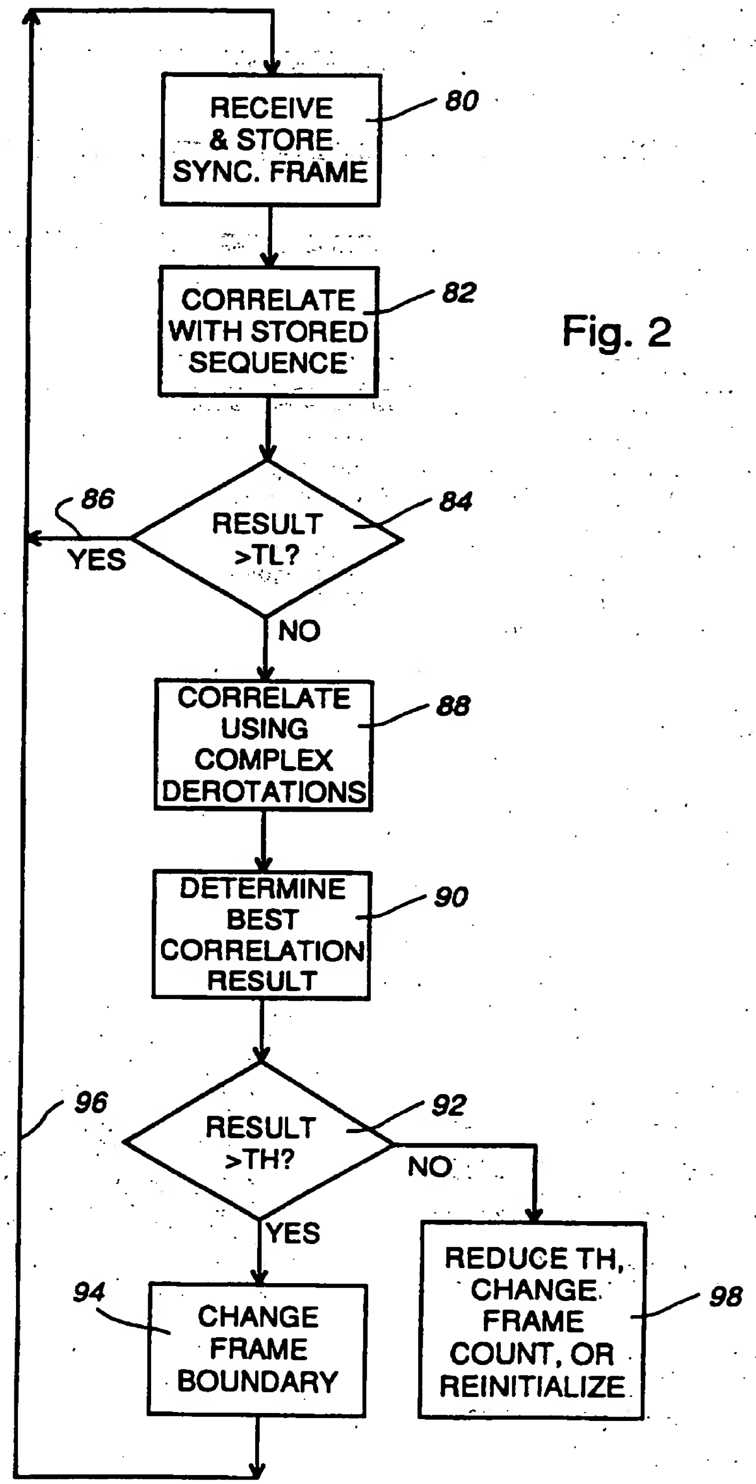

RECEIVE & STORE SYNC. FRAME
80
CORRELATE WITH STORED SEQUENCE
82
RESULT >TL?
84
86
YES
NO
CORRELATE USING COMPLEX DEROTATIONS
88
DETERMINE BEST CORRELATION RESULT
90
RESULT >TH?
92
96
NO
YES
CHANGE FRAME BOUNDARY
94
REDUCE TH, CHANGE FRAME COUNT, OR REINITIALIZE
98

Fig. 2

INTERNATIONAL SEARCH REPORT

Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-9505042	16-02-95	US-A-	5444697	22-08-95
		AU-B-	7454794	28-02-95